High-Fidelity Medical Imaging Displays
High-Fidelity Medical Imaging Displays, Aldo Badano, Michael J. Flynn, and Jerzy Kanicki, Vol. TT63
Diffractive Optics—Design, Fabrication, and Test, Donald C. O’Shea, Thomas J. Suleski, Alan D. Kathman, and Dennis W. Prather, Vol. TT62
Thin-Film Design: Modulated Thickness and Other Stopband Design Methods, Bruce Perilloux, Vol. TT57
Optische Grundlagen für Infrarotsysteme, Max J. Riedl, Vol. TT56
An Engineering Introduction to Biotechnology, J. Patrick Fitch, Vol. TT55
Image Performance in CRT Displays, Kenneth Compton, Vol. TT54
Modulation Transfer Function in Optical and Electro-Optical Systems, Glenn D. Boreman, Vol. TT52
Fundamentals of Antennas, Christos G. Christodoulou and Parveen Wahid, Vol. TT50
Basics of Spectroscopy, David W. Ball, Vol. TT49
Resolution Enhancement Techniques in Optical Lithography, Alfred Kwok-Kit Wong, Vol. TT47
Copper Interconnect Technology, Christoph Steinbrüchel and Barry L. Chin, Vol. TT46
Fundamentals of Contamination Control, Alan C. Tribble, Vol. TT44
Evolutionary Computation: Principles and Practice for Signal Processing, David Fogel, Vol. TT43
Infrared Optics and Zoom Lenses, Allen Mann, Vol. TT42
Introduction to Adaptive Optics, Robert K. Tyson, Vol. TT41
Fractal and Wavelet Image Compression Techniques, Stephen Welstead, Vol. TT40
Tissue Optics: Light Scattering Methods and Instruments for Medical Diagnosis, Valery Tuchin, Vol. TT38
Infrared Design Examples, William L. Wolfe, Vol. TT36
Design and Mounting of Prisms and Small Mirrors in Optical Instruments, Paul R. Yoder, Jr., Vol. TT32
Basic Electro-Optics for Electrical Engineers, Glenn D. Boreman, Vol. TT31
Optical Engineering Fundamentals, Bruce H. Walker, TT Vol. 30
Introduction to Radiometry, William L. Wolfe, Vol. TT29
Lithography Process Control, Harry J. Levinson, Vol. TT28
An Introduction to Interpretation of Graphic Images, Sergey Ablameyko, Vol. TT27
Thermal Infrared Characterization of Ground Targets and Backgrounds, P. Jacobs, Vol. TT26
Introduction to Imaging Spectrometers, William L. Wolfe, Vol. TT25
Optical Communication Receiver Design, Stephen B. Alexander, Vol. TT22
Mounting Lenses in Optical Instruments, Paul R. Yoder, Jr., Vol. TT21
High-Fidelity Medical Imaging Displays

Aldo Badano
Michael J. Flynn
Jerzy Kanicki

Tutorial Texts in Optical Engineering
Volume TT63

SPIE PRESS
Bellingham, Washington USA
Introduction to the Series

Since its conception in 1989, the Tutorial Texts series has grown to more than 60 titles covering many diverse fields of science and engineering. When the series was started, the goal of the series was to provide a way to make the material presented in SPIE short courses available to those who could not attend, and to provide a reference text for those who could. Many of the texts in this series are generated from notes that were presented during these short courses. But as stand-alone documents, short course notes do not generally serve the student or reader well. Short course notes typically are developed on the assumption that supporting material will be presented verbally to complement the notes, which are generally written in summary form to highlight key technical topics and therefore are not intended as stand-alone documents. Additionally, the figures, tables, and other graphically formatted information accompanying the notes require the further explanation given during the instructor’s lecture. Thus, by adding the appropriate detail presented during the lecture, the course material can be read and used independently in a tutorial fashion.

What separates the books in this series from other technical monographs and textbooks is the way in which the material is presented. To keep in line with the tutorial nature of the series, many of the topics presented in these texts are followed by detailed examples that further explain the concepts presented. Many pictures and illustrations are included with each text and, where appropriate, tabular reference data are also included.

The topics within the series have grown from the initial areas of geometrical optics, optical detectors, and image processing to include the emerging fields of nanotechnology, biomedical optics, and micromachining. When a proposal for a text is received, each proposal is evaluated to determine the relevance of the proposed topic. This initial reviewing process has been very helpful to authors in identifying, early in the writing process, the need for additional material or other changes in approach that would serve to strengthen the text. Once a manuscript is completed, it is peer reviewed to ensure that chapters communicate accurately the essential ingredients of the processes and technologies under discussion.

It is my goal to maintain the style and quality of books in the series, and to further expand the topic areas to include new emerging fields as they become of interest to our reading audience.

Arthur R. Weeks, Jr.
University of Central Florida
# Contents

<table>
<thead>
<tr>
<th>List of Figures</th>
<th>xi</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Tables</td>
<td>xv</td>
</tr>
<tr>
<td>Preface</td>
<td>xvii</td>
</tr>
<tr>
<td>Chapter 1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Medical Imaging Display Markets</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Units of Measure</td>
<td>2</td>
</tr>
<tr>
<td>Chapter 2 High-Fidelity Display Performance</td>
<td>5</td>
</tr>
<tr>
<td>2.1 Contrast Sensitivity</td>
<td>5</td>
</tr>
<tr>
<td>2.2 Luminance Response</td>
<td>7</td>
</tr>
<tr>
<td>2.3 Luminance Range</td>
<td>9</td>
</tr>
<tr>
<td>2.4 Adaptation</td>
<td>9</td>
</tr>
<tr>
<td>2.5 Retinal Anatomy and Visual Acuity</td>
<td>10</td>
</tr>
<tr>
<td>2.6 Veiling Glare</td>
<td>13</td>
</tr>
<tr>
<td>2.6.1 Glare in the human eye</td>
<td>13</td>
</tr>
<tr>
<td>2.6.2 Veiling glare in displays</td>
<td>14</td>
</tr>
<tr>
<td>2.6.2.1 Sources of glare</td>
<td>14</td>
</tr>
<tr>
<td>2.6.2.2 Effect of veiling glare</td>
<td>17</td>
</tr>
<tr>
<td>2.7 Ambient Light Reflections</td>
<td>18</td>
</tr>
<tr>
<td>2.7.1 Specular reflection</td>
<td>19</td>
</tr>
<tr>
<td>2.7.2 Diffuse reflection</td>
<td>21</td>
</tr>
<tr>
<td>2.8 High-Fidelity Display Requirements</td>
<td>22</td>
</tr>
<tr>
<td>Chapter 3 Cathode-Ray Tubes</td>
<td>25</td>
</tr>
<tr>
<td>3.1 Cathodes</td>
<td>26</td>
</tr>
<tr>
<td>3.2 Electron Optics</td>
<td>28</td>
</tr>
<tr>
<td>3.3 Emissive Structure</td>
<td>28</td>
</tr>
<tr>
<td>3.4 Signal Electronics</td>
<td>29</td>
</tr>
<tr>
<td>3.5 Color CRTs</td>
<td>32</td>
</tr>
<tr>
<td>3.6 Spot Size</td>
<td>33</td>
</tr>
<tr>
<td>3.7 Monochrome Phosphors</td>
<td>34</td>
</tr>
<tr>
<td>3.8 Antireflection Surface Treatments</td>
<td>35</td>
</tr>
<tr>
<td>3.9 Face-plate Absorption</td>
<td>36</td>
</tr>
<tr>
<td>3.10 Gray-scale Controllers</td>
<td>36</td>
</tr>
</tbody>
</table>
# Chapter 4 Active-Matrix Liquid Crystal Displays

4.1 The Liquid Crystal Cell .............................................. 40
4.2 Efficiency of Light Transmission ................................. 42
4.3 Addressing Methods ................................................. 43
4.4 Elements of an AMLCD ............................................. 44
4.5 Crosstalk in AMLCDs ............................................... 47
4.6 Luminance Variations with Viewing Angle ....................... 48
4.7 Solutions to Viewing Angle Problem ............................... 51
  4.7.1 Compensation foils .......................................... 51
  4.7.2 Multiple domain cells ..................................... 52
  4.7.3 Symmetry micro-cells ...................................... 53
  4.7.4 In-plane switching .......................................... 53
  4.7.5 Vertical alignment .......................................... 54

# Chapter 5 Active-Matrix Organic Light-Emitting Displays

5.1 Introduction to OLEDs ............................................ 55
  5.1.1 History of OLEDs ........................................... 56
  5.1.2 OLEDs for displays ....................................... 57
  5.1.3 OLED structures ........................................... 58
  5.1.4 EL organic materials ...................................... 62
5.2 Evaluation of Device Opto-Electronic Performance ............. 65
5.3 Device Configuration and Display Fabrication ................. 65
  5.3.1 Conventional OLED ........................................ 66
  5.3.2 Side-by-side subpixels .................................... 67
  5.3.3 White OLED filtering ..................................... 67
  5.3.4 Blue OLED down-conversion ............................. 69
  5.3.5 Microcavity OLEDs ....................................... 69
  5.3.6 Color-tunable OLEDs .................................... 70
  5.3.7 Pyramid-shaped pixel OLEDs ............................ 70
  5.3.8 Stacked OLEDs ............................................ 71
5.4 OLED Stability and Encapsulation for Displays ................. 74
  5.4.1 Impact of moisture and oxygen ............................ 74
  5.4.2 Influence of dark spots .................................... 77
  5.4.3 Encapsulation methods .................................... 79
5.5 Display Addressing and Driving Circuit ......................... 81
  5.5.1 PM-addressing method ..................................... 82
  5.5.2 AM-addressing method .................................... 84
5.6 TFT Technology for AM Displays ................................ 85
  5.6.1 a-Si:H TFT technology ..................................... 86
  5.6.2 Poly-Si TFT Technology .................................... 87
  5.6.3 Pixel electrode circuits .................................... 88
5.7 Methods to Improve AMOLED Contrast Ratio .................... 100
## 5.8 Current Market and Future Trends .......................... 101
  5.8.1 Comparison between OLED and non-LED displays ........ 101
  5.8.2 Comparison between OLEDs and inorganic LEDs .......... 103
  5.8.3 Current and future challenges ......................... 103

### Chapter 6 Display Image Quality Metrics ........................ 105

  6.1 Luminance Response ........................................ 105
     6.1.1 Luminance calibration ............................... 107
     6.1.2 Angular emission .................................... 109
  6.2 Contrast Ratio .............................................. 114
     6.2.1 Veiling glare ......................................... 114
     6.2.2 Electronic crosstalk .................................. 116
  6.3 Spatial Frequency ............................................ 123
  6.4 Noise .......................................................... 125
  6.5 Reflectance ................................................... 129
     6.5.1 Reflectance models ................................. 130
     6.5.2 Measuring display reflections ....................... 131
     6.5.3 Bidirectional reflection distribution function ....... 135
  6.6 Evaluation Software and Standards ......................... 136

### References ....................................................... 139

### Index ............................................................ 151
## List of Figures

1.1 Number of display devices offering new technology (1997–2002) .... 3

2.1 Visual contrast threshold as a function of luminance ............... 7
2.2 A perceptually linear display function ............................. 8
2.3 Adaptation of the photoreceptors .................................. 10
2.4 Luminance range for good contrast response ...................... 11
2.5 Effect of the spatial frequency of the stimulus on vision threshold 12
2.6 Scattering of a beam of light entering the eye .................... 14
2.7 Veiling glare in the human eye .................................... 15
2.8 Radiographic images showing significant veiling glare effects .... 16
2.9 Schematic representation of the three sources of veiling glare .... 16
2.10 Image test pattern to illustrate and measure veiling glare effects 18
2.11 Radiological workstation with poor room illumination control 19
2.12 Specular and diffuse reflections for a CRT .......................... 19
2.13 Contrast reduction from diffuse added luminance ................ 20

3.1 The major components of a CRT .................................... 26
3.2 Reduction in electron emission due to aging of CRT cathodes ...... 27
3.3 Thermionic cathodes found in high-performance CRTs ........... 27
3.4 Einzel lens arrangement used in the CRT electron gun ........... 28
3.5 Emissive structure of a CRT ...................................... 29
3.6 Components of the CRT emissive structure .......................... 30
3.7 Transformation of the input signal into the luminance field in a CRT 30
3.8 Deflection of the electron beam .................................... 31
3.9 Emissive structure of a color CRT .................................. 32
3.10 Designs for achieving color in a CRT ............................... 32
3.11 Degradation of luminance and color contrast in a color CRT .... 33
3.12 Reduction of the display luminance due to phosphor aging ...... 35
3.13 Antireflection properties of a multilayer thin-film coating ....... 35
3.14 Reduction of ambient light reflections using tinted glass .......... 36
3.15 Precision of a gray-scale presentation ............................. 37
3.16 The DVI TMDS layers .............................................. 37
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Alignment of LC molecules along the director</td>
<td>40</td>
</tr>
<tr>
<td>4.2</td>
<td>Change in LC orientation due to an external electric field</td>
<td>41</td>
</tr>
<tr>
<td>4.3</td>
<td>The LC electro-optical effect that defines light transmission</td>
<td>41</td>
</tr>
<tr>
<td>4.4</td>
<td>Elements of a typical LCD</td>
<td>42</td>
</tr>
<tr>
<td>4.5</td>
<td>Power efficiency and brightness reduction in an AMLCD</td>
<td>42</td>
</tr>
<tr>
<td>4.6</td>
<td>Addressing methods for an AMLCD</td>
<td>43</td>
</tr>
<tr>
<td>4.7</td>
<td>Cross section of a color AMLCD showing typical components</td>
<td>45</td>
</tr>
<tr>
<td>4.8</td>
<td>Typical TFT response curve with high ON/OFF ratio</td>
<td>46</td>
</tr>
<tr>
<td>4.9</td>
<td>Pixel layout defining the aperture ratio and the TFT</td>
<td>46</td>
</tr>
<tr>
<td>4.10</td>
<td>Effect of crosstalk on a displayed image</td>
<td>47</td>
</tr>
<tr>
<td>4.11</td>
<td>Cross section of an AMLCD</td>
<td>48</td>
</tr>
<tr>
<td>4.12</td>
<td>Display luminance curves as a function of the viewing direction</td>
<td>49</td>
</tr>
<tr>
<td>4.13</td>
<td>Display contrast expressed as a function of the viewing direction</td>
<td>50</td>
</tr>
<tr>
<td>4.14</td>
<td>Compensation films used to improve the viewing angle of an AMLCD</td>
<td>52</td>
</tr>
<tr>
<td>4.15</td>
<td>Advanced designs of LCD cells</td>
<td>53</td>
</tr>
<tr>
<td>5.1</td>
<td>Schematic of an OLED</td>
<td>58</td>
</tr>
<tr>
<td>5.2</td>
<td>Typical internal quantum efficiencies for OLEDs</td>
<td>59</td>
</tr>
<tr>
<td>5.3</td>
<td>The hole-injection layer and the chemical structures of the polymer</td>
<td>61</td>
</tr>
<tr>
<td>5.4</td>
<td>EL emission of a typical polymer</td>
<td>64</td>
</tr>
<tr>
<td>5.5</td>
<td>Conventional OLED structure</td>
<td>66</td>
</tr>
<tr>
<td>5.6</td>
<td>Five full-color subpixel configurations</td>
<td>68</td>
</tr>
<tr>
<td>5.7</td>
<td>Schematic cross-section of an OLED</td>
<td>70</td>
</tr>
<tr>
<td>5.8</td>
<td>Different structures of pyramid-shaped pixels</td>
<td>71</td>
</tr>
<tr>
<td>5.9</td>
<td>R, G, and B OLED emission</td>
<td>72</td>
</tr>
<tr>
<td>5.10</td>
<td>Stacked OLED (SOLED)</td>
<td>73</td>
</tr>
<tr>
<td>5.11</td>
<td>Transmission of PPV under air, water vapor, and a vacuum</td>
<td>76</td>
</tr>
<tr>
<td>5.12</td>
<td>XPS spectrum of an OLED</td>
<td>76</td>
</tr>
<tr>
<td>5.13</td>
<td>Time evolution of dark spots</td>
<td>77</td>
</tr>
<tr>
<td>5.14</td>
<td>EL spectra showing dark spot formation</td>
<td>78</td>
</tr>
<tr>
<td>5.15</td>
<td>A propagation mechanism of dark spots</td>
<td>78</td>
</tr>
<tr>
<td>5.16</td>
<td>Schematic cross-section of an encapsulated OLED</td>
<td>79</td>
</tr>
<tr>
<td>5.17</td>
<td>Cross-section side view of an encapsulated OLED</td>
<td>80</td>
</tr>
<tr>
<td>5.18</td>
<td>Side view of an encapsulated OLED</td>
<td>80</td>
</tr>
<tr>
<td>5.19</td>
<td>Cross section of an encapsulated OLED</td>
<td>81</td>
</tr>
<tr>
<td>5.20</td>
<td>Matrix addressing of an OLED</td>
<td>82</td>
</tr>
<tr>
<td>5.21</td>
<td>Equivalent circuit of the PM-addressing scheme</td>
<td>83</td>
</tr>
<tr>
<td>5.22</td>
<td>AM-addressing using two TFTs per pixel</td>
<td>84</td>
</tr>
<tr>
<td>5.23</td>
<td>Fabrication process for an a-Si:H-based TFT AM pixel</td>
<td>87</td>
</tr>
<tr>
<td>5.24</td>
<td>Cross section of a poly-Si TFT AM pixel</td>
<td>88</td>
</tr>
<tr>
<td>5.25</td>
<td>Pixel electrode circuit for an AMLCD and an AMOLED</td>
<td>88</td>
</tr>
<tr>
<td>5.26</td>
<td>Area ratio gray scale (ARGS) method</td>
<td>91</td>
</tr>
<tr>
<td>5.27</td>
<td>Two types of voltage-driven electrode circuits</td>
<td>92</td>
</tr>
</tbody>
</table>
List of Figures

5.28 Two types of current-programming, current-driven pixel electrode circuits ........................................ 94
5.29 Two types of current-mirror, current-driven pixel electrode circuits ...................................................... 95
5.30 A current-sink, current-driven pixel electrode circuit ............................................................................. 96
5.31 Bottom-emission and top-emission pixel electrode configurations ..................................................... 97
5.32 A four-TFT AM pixel electrode circuit ................................................................................................. 98
5.33 Discrimination ratio versus OLED reflectance curves .......................................................................... 101
5.34 Comparison between OLEDs and inorganic LEDs ............................................................................ 103

6.1 Grey-scale display function ................................................................................................................. 108
6.2 Data in Fig. 6.1 presented in terms of luminance change at each level .................................................. 108
6.3 Variation of $L_{min}$ measurements due to veiling glare ....................................................................... 109
6.4 Setup for automatic measurement of luminance response ............................................................... 110
6.5 Evaluation of the luminance response across the 256 gray levels ................................................. 110
6.6 Experimental setup to measure angular luminance ........................................................................... 111
6.7 Data analysis for compliance with DICOM 3.14 GSDF ................................................................. 112
6.8 Setup to measure angular luminance using Fourier optics ............................................................... 113
6.9 Method to measure the RRF ............................................................................................................. 115
6.10 The conic collimated probe for measuring veiling glare ................................................................. 117
6.11 Experimental setup for measuring veiling glare .............................................................................. 118
6.12 The RRF of four CRTs ...................................................................................................................... 118
6.13 Test patterns for crosstalk measurements .......................................................................................... 120
6.14 Crosstalk response functions ............................................................................................................. 122
6.15 Profile of a CRT beam spot ............................................................................................................... 123
6.16 Measured MTFs at two luminance levels and two orientations ....................................................... 125
6.17 Photographs of CRT screens using a macro lens .............................................................................. 127
6.18 NPS measurements for P104 and P45 CRT phosphors .................................................................. 127
6.19 Single-pixel images of a CRT and an AMLCD ............................................................................... 128
6.20 NPS measurements for AMLCDs and CRTs using apertures ....................................................... 128
6.21 Small spot lamp used as a light source for specular reflections ...................................................... 131
6.22 Portable white room viewed through a hole ....................................................................................... 132
6.23 White reflective box for diffuse reflection measurements ................................................................ 133
6.24 One-dimensional reflection signature of an AMLCD .................................................................... 136
6.25 DisplayTool opening window .......................................................................................................... 137
List of Tables

2.1 Number of achievable JNDs for display devices ......................... 8
2.2 Pixel sizes corresponding to spatial acuity of the human visual system . 12
2.3 Ambient illumination required for maintaining specular reflections .... 20
2.4 Typical ambient illumination levels ...................................... 21
2.5 Ambient illumination for maintaining 80% of the available contrast .. 22
2.6 Display requirements for medical imaging applications ................. 23

3.1 Bandwidth required at the deflection amplifiers ....................... 31
3.2 Beam spot size for a 300 × 400-mm field with a 50% overlap ......... 34
3.3 Beam spot size for a 270 × 330-mm field with a 50% overlap ......... 34

4.1 TFT technologies used for AMLCDs ..................................... 45

5.1 Specifications of AMOLED prototypes .................................. 56
5.2 Comparison of traditional and polymeric semiconductors .............. 63
5.3 Summary of subpixel structures used to achieve full-color displays . . 75
5.4 Comparison of a-Si:H and poly-Si TFT properties ..................... 86
5.5 Comparison of LT poly-Si and a-Si:H TFT properties .................. 89
5.6 Comparison between voltage-driven and current-driven AMOLEDs . . 99
5.7 Worldwide OLED market by application .............................. 102

6.1 Maximum and minimum luminance of typical display devices ........ 106
6.2 Diffuse reflection coefficients for typical display devices ............. 106
6.3 Measured G for medical and graphic arts workstation monitors ...... 115
6.4 Fundamental technological differences between CRTs and AMLCDs . . 126
6.5 Reflection coefficients for high-performance display devices ........ 134
Preface

This book is based on a short course given by the authors at SPIE’s Medical Imaging International Symposium from 1999 to 2002. During those years, the number of commercially available medical display systems increased considerably. For instance, during the 84th annual meeting of the Radiological Society of North America (RSNA) held in Chicago in 1998, three different liquid crystal prototypes were showcased on the commercial exhibit floor by just a few vendors. In the 88th RSNA meeting held in the same city in 2002, more than 20 different liquid crystal technologies in more than 100 models were present on the exhibit floor.

At the same time, we have witnessed a significant increase in the interest level of the community about display system performance and application requirements. We have also experienced an exciting feeling that this is just the beginning of a rapidly evolving story that will be nurtured by new technologies and new applications. The number of modalities that rely on the electronic presentation of image data is growing rapidly, including computed tomography, mammography, chest and bone radiography, ultrasound, and image-guided interventional procedures. Moreover, this growth has been emphasized by the availability of powerful computer networks that allow remote users to receive large image datasets and display them in their portable computers or personal digital appliances. This changing scenario also brings challenges regarding how these devices and systems are used, and about how physical measurements can be used to assess image quality. It is in this spirit that we present in this book the expanded content of the short course.

This book is organized into six chapters. Chapters 1 and 2 introduce medical imaging displays by defining the requirements for a high-fidelity display performance, and by summarizing human visual system characteristics with respect to luminance, contrast, resolution, glare, and reflection. Chapters 3 and 4 introduce the different display technologies that have, or are likely to have, an impact on medical imaging workstations today or in the future. Chapter 3 presents a review of the ubiquitous cathode-ray tube (CRT), and Chapter 4 describes the active-matrix liquid crystal display (AMLCD). Chapter 5 presents the current challenges in the development of an emerging display technology based on light-emitting organic molecules and polymer devices that will likely be present in many portable display solutions in the coming few years. Having described the requirements for a high-fidelity display and its intrinsic device properties, we develop, in Chapter 6, methods for the assessment of display image quality. In this chapter, we focus on meth-
ods that are useful to characterize display performance while allowing the measurement of image quality up to, and even beyond, the limits of the human visual system.

Most of the methods presented in this book are described in a way that clinical engineers and medical physicists can utilize them in a clinical environment as long as they have access to the appropriate instrumentation. This tutorial is not, however, a collection of ready-to-use procedures or techniques. Readers interested in more practical aspects of display quality assessment should consider the recommendations of the American Association of Physicists in Medicine (AAPM), or the collection of measurement methods assembled in the Flat Panel Display Measurement Standard. Our perspective in this book is to offer a more general tutorial on display image quality, its relationship to device technology, and the methodologies for its assessment. At the same time, the methods and techniques described will allow other readers who are involved in the design, manufacture, marketing, purchase, and management of displays for digital radiology systems to make informed decisions about display devices and display image quality by better understanding the device requirements and specifications.

Much of the effort in this book was supported by the Center for Devices and Radiological Health (CDRH) from the Food and Drug Administration (FDA), the National Institutes of Health (NIH), and the Defense Advanced Research Projects Agency (DARPA). I would like to express our thanks to the many reviewers of the manuscript in its various forms including Rachel Leimbach, Susan Hipper, Ben Imhoff, and Sarah Drilling—all student interns from the Department of Biomedical Engineering at Marquette University. We are also thankful for the useful discussions with Ehsan Samei (Duke University), Sandrine Martin (University of Michigan), Ken Compton (National Display Systems), Robert J. Jennings (CDRH, FDA), Robert M. Gagne (CDRH, FDA), Kyle J. Myers (CDRH, FDA), and Robert F. Wagner (CDRH, FDA) that have made this book better.

Aldo Badano
July 2004